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Cost and Performance Report

(CP-9906)

Reduction of Diesel Engine Particulate Emissions Using a Self-Regenerating Soot Filter

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LIST OF ACRONYMS

AFB	Air Force Base
BC	Black Carbon
CARB	California Air Resources Board
CAVTC	Clean Air Vehicle Technology Center
CCR	California Code of Regulations
CBD	Central Business District
CFR	Code of Federal Regulations
CLSF	Conventional Low Sulfur Fuel
CO	Carbon Monoxide
CRT	Continuously Regenerating Trap
CSF	Catalyzed Soot Filters
Cu.ft.	Cubic Feet
DOC	Diesel Oxidation Catalyst
DoD	Department of Defense
DT	Dust Track
EGR	Engine Gas Recirculation
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
F.E.	Fuel Economy
g/bhp-hr	Gram Per Brake Horsepower Hour
g/mile	Gram Per Mile
GSA	General Services Administration
HC	Hydrocarbon
Hg	Mercury
HP	Horsepower
KW	Kilowatt
MTU	Michigan Technological University
NFESC	Naval Facilities Engineering Service Center
NO_x	Nitrous Oxide Chemical Compounds
NO_2	Nitrogen Dioxide
NYBC	New York Bus Cycle

LIST OF ACRONYMS (continued)

OEM	Original Equipment Manufacturer
OPC	Optical Particle Counter
PA	Photoacoustic Analyzer
PAH	Polycyclic Aromatic Hydrocarbon
PAS	Photoelectric Aerosol Sensor
PM	Particulate Matter
PPM	Parts Per Million
POC	Point of Contact
Pt	Platinum
SAE	Society of Automotive Engineers
SERDP	Strategic Environmental Research and Development Program
SMPS	Scanning Mobility Particle Sizer
SO_2	Sulfur Dioxide
SO_4^{-2}	Sulfate
SOF	Soluble Organic Fraction
THC	Total Hydrocarbon
TPM	Total Particulate Matter
UDDS	Urban Dynamometer Driving Schedule
ULEV	Ultra Low Emission Vehicle
ULSF	Ultra Low Sulfur Fuel

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Our appreciation is also extended to the University of Utah diesel engine particulate testing team consisting of Dr. Adel Sarofim, Dr. JoAnn Lighty, Kerry Kelly, and Dave Wagner as well as Klaus Peter, Dr. Osama Ibrahim, Zack Nardi, and Frank DePetrillo from Rypos, Inc., the supplier of the active soot filters.

1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

Diesel engines are widely used throughout the Department of Defense (DoD) for powering tactical and non-tactical vehicles and vessels, off-road equipment, engine-generator sets, aircraft ground-support equipment, and a variety of other applications. Although diesel engines, like gasoline engines, are known to emit several types of pollutants into the atmosphere, human health concerns regarding the penetration of the small particulate matter (PM) [specifically those having diameters of less than 2.5 microns, designated PM2.5] into the deeper regions of the lungs have greatly increased interest in diesel PM emissions in the recent past. Diesel engine particulate matter emissions are regulated as a criterion pollutant by the National Ambient Air Quality Standards (NAAQS) established by the Clean Air Act. In addition, new rules have been promulgated that will require particulate matter emission reductions.

For more than a decade, investigators have developed the use of soot filters to reduce PM emissions from diesel engines. However, important unresolved technical and economic problems have plagued these filters and prevented their widespread application. The most important of these problems is the complete oxidation of the soot trapped in the filter on-line during engine operation, a phenomenon termed "regeneration". Two soot filter systems were tested the Naval Facilities Engineering Service Center (NFESC) during this ESTCP demonstration to address this issue: the Engelhard Catalyzed Soot Filter (CSF), and the Rypos electrically regenerating soot filter. During this project, 10 DoD diesel engines were retrofitted with these filters and field-tested under normal operating conditions.

The CSF used in this demonstration contains a porous cordierite ceramic substrate in the exhaust gas flow path. The particulate matter is captured within the ceramic and is oxidized to carbon dioxide by the thermal energy of the exhaust. The use of the catalyst allows for the oxidation to proceed at exhaust temperatures as low as 360°C. The Rypos trap consists of a non-catalyzed sintered metallic fiber media. Using the resistive properties of the media, an electric current can be supplied to regenerate the filter. The advantage of this system is that the filter does not rely on high exhaust gas temperatures to regenerate.

1.2 REGULATORY DRIVERS

Mobile-source diesel emissions are regulated by both Federal (40 CFR 85, 86, 89, 94) and California (13 CCR Chapter 3) equipment and vehicle standards. Those standards are applied to equipment and vehicles at the time of manufacture. In the last five years, the Environmental Protection Agency (EPA) has pursued a program to dramatically tighten these regulations. This is illustrated in Table 1, which shows the 2007 EPA heavy-duty on-road engine standards, along with the year 2000 standards.

Table 1. Current and Future EPA Highway Emissions Regulations [g/bhp[hr].

		2000	2007 Onwards	2007	2008	2009	2010
Diesel Fleet	NO_x	4.0	0.20	25%	50%	75%	100%
	HC	1.3	0.14				
	CO	15.5	15.5	100%	100%	100%	100%
	PM	0.10	0.01	100%	100%	100%	100%

Note: Percentages represent percent of sales

The 2007 heavy-duty highway diesel engine standards will reduce PM emissions by about 98% from a 1990 baseline and 90% from a 2000 baseline. Significant nitrous oxide chemical compounds (NO_x) and hydrocarbon (HC) reductions are also required for 2007 and later engines. However, because these emissions decreases do not affect existing diesel engines, the full benefit will take more than 20 years to achieve. In an effort to achieve the benefits sooner, several states have proposed regulatory strategies to reduce emissions for existing engines.

In October 2000, the California Air Resources Board (CARB) finalized their plan, *Risk Reduction Plan to Reduce Particulate Matter Emissions from Diesel-Fueled Engines and Vehicles.* The California plan calls for the use of low-sulfur fuels, retrofit requirements or the replacement of existing engines for on-road, non-road, portable, and stationary equipment. In addition, California has proposed programs to encourage equipment owners to voluntarily retrofit equipment with particulate filters.

Stationary-source diesel emissions are regulated by state and local regulations. Currently, most regulations only limit NO_x, carbon monoxide (CO) and opacity. However, CARB recently proposed guidance that, if adopted by local air districts, would require use of low-sulfur diesel fuel and catalyst-based diesel particulate filters.

Currently, particulate emissions have been controlled primarily through engine management. Some applications have implemented a diesel oxidation catalyst (DOC); however, DOCs only provide maximum reductions of 50% of the total particulate matter, with most of that portion being the organic fraction of the particulates. These high reductions would only occur on older engines that have much higher organic fractions. DOCs reduce the carbonaceous fraction to a small extent.

1.3 OBJECTIVES OF THE DEMONSTRATION

The primary objective of this demonstration is to reduce particulate emissions by 90%. Accomplishing this objective will bring on-road engines, certified between 1994 and 2002, to the proposed 2007 PM standard of 0.01 g/bhp-hr. Hydrocarbon (HC) and CO emissions reductions of 75% and 50%, respectively, are also proposed for catalyzed filters.

1.4 DEMONSTRATION RESULTS

To demonstrate the soot filter technology, 10 diesel engines, all located at DoD field activities in southern California, were used. Eight of the engines were installed in on-road vehicles, while the

other two were installed in tactical diesel generators. All of the demonstration engines were tested using their normal duty cycle, which are characteristic of many potential DoD applications.

For the CSFs, a greater than 90% particulate matter emission reduction was achieved on engines certified at the 0.1 g/bhp-hr level, thereby reducing tailpipe emissions to the 0.01 g/bhp-hr level. The Rypos traps exhibited a 62% average reduction in particulate emissions. The Engelhard CSFs also demonstrated a minimum HC and CO reduction of 72% and 49%, respectively.

This project addressed evolving emissions standards. As such, the treatment costs are additional to current operating or capital costs of the vehicles. The capital costs for the soot filter technology are dependent on the size and use of the engine and the number of similar engines modified. Since the application of the soot filters to each vehicle is unique, costs will vary. The two soot filter systems chosen for this study were the most suitable based on maturity of product, availability, and tolerance of the current fuel sulfur levels. The installed capital costs of the two filter systems were $7,050 and $9,500 with annual operation and maintenance costs of $300-$400.

1.5 STAKEHOLDER/END-USER ISSUES

Throughout the project, a number of stakeholders were identified. The addition of soot filter systems presents an additional capital cost to both the engine and vehicle manufacturer, and thus, the end-user (i.e., vehicle owner/driver). For the vehicle owner, a small increase in fuel costs may also result. This slight fuel penalty is a result of the inherent backpressure placed on the engine by the filter and, therefore, more fuel is required to sustain the same power. In addition, periodic maintenance of the systems will be necessary to clean ash out of the filter. However, the target frequency of this operation would be greater than 50,000 miles. Despite some of these issues, there is a benefit to applying the soot filter technology since some particulate matter has been shown to cause adverse health effects, and soot filters can reduce current emissions by 90% or more.

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2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

Soot filters are installed on exhaust systems downstream of a diesel engine and can significantly reduce particulate emissions. The concept of soot filtration is applicable to every diesel engine application.

CSFs are typically composed of a ceramic substrate impregnated or washcoated with a platinum-based catalyst. Engelhard was one of the first companies to introduce this technology. For low catalyst loading levels, the trapped soot can be oxidized at temperatures as low as 360°C, in essence, cleaning the filter in a process termed "regeneration." This regeneration method is referred to as passive since no external heat energy enters into the system to achieve soot oxidation. Rather, the system relies on the duty cycle of the engine to generate sufficiently high temperatures to initiate soot combustion. Such a system is shown in Figure 1.

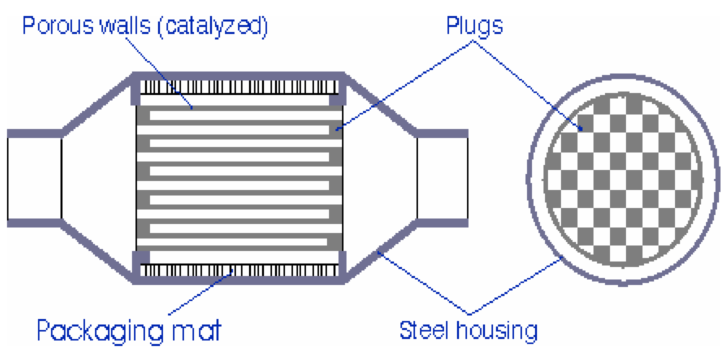

Figure 1. Passive Catalyzed Soot Filter.

Many light duty engines do not generate exhaust temperatures conducive to passive regeneration of soot filters. Even heavy duty engines operating under light load conditions or in cold weather, can result in partial or complete plugging of the filter, thereby inducing high engine back-pressures, reduced engine power and unsuccessful vehicle operation. Moreover, when loaded heavily with soot, the filter can be damaged when idle conditions occur subsequent to high load operation. In this case, combustion of the trapped soot begins at the high load condition, however when the engine is then idled, there is an insufficient amount of exhaust flow to carry away the heat, and the trap could melt. This occurrence is called "uncontrolled regeneration".

Such circumstances may be prevented by implementing an active regeneration system to apply external sources of heat energy, such that excessive amounts of soot are not collected by the filter.

The Rypos active soot filter system is one such system that applies an electrical current to supply the heat energy to oxidize the soot, and thus, regenerate the filter. Electrical regeneration has been under development by various companies for over 10 years. Rypos is using a novel approach to electrically regenerate a filter. The Rypos system uses a sintered metal fiber media that acts as the substrate to capture particulate matter, as well as the resistive element by which an electric current can be supplied to produce the heat to oxidize the soot. This material is unique in that it performs both functions, thereby reducing system size and manufacturing cost. The filter is composed of multiple cartridges that are regenerated separately and sequentially, thus reducing the amount of electrical energy required at any one point in time. This relates to lower instantaneous power consumption and fuel penalty. A schematic of the Rypos system is shown in Figure 2.

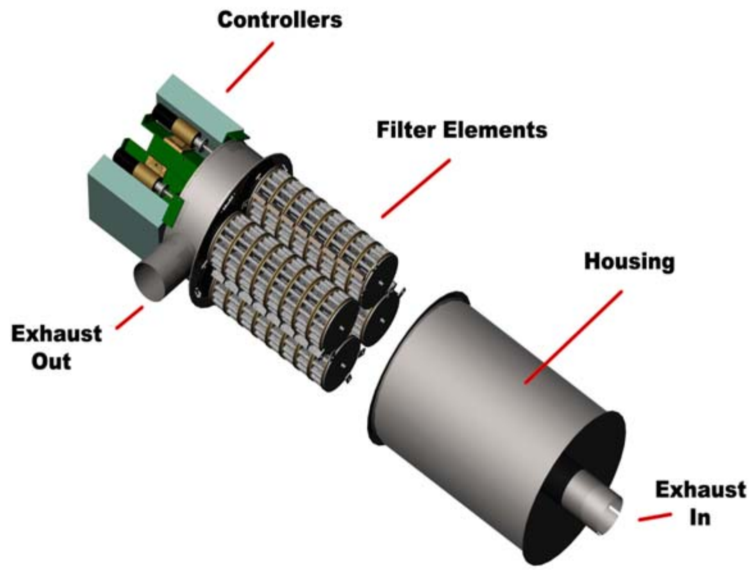

Figure 2. Rypos Electrically Regenerating Particulate Trap.

2.2 PROCESS DESCRIPTION

With installations for retrofit and original equipment manufacturer (OEM) applications, the soot filter is expected to replace the muffler since it provides satisfactory sound attenuation. With respect to electrical active systems, an additional power source must be found or installed on the vehicle, such as a larger or second alternator. On-board diagnostics and alarms would also be installed to indicate trap performance and condition. Once installed, trap operation is transparent to the driver or operator.

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

Initial field tests of the CSF were completed on eight urban buses operated by the New Jersey Transit Authority. Results demonstrated a CSF lifetime greater than one year (>100,000 miles) and PM emission reductions greater than 80 percent. Some soot filter failures were also noted during this program, indicating the importance of monitoring the condition of the soot filter and performing routine maintenance.

The effectiveness of a soot filter in reducing the total mass is evident from Figure 3. This figure depicts two sampling filter papers from a double dilution tunnel system. One paper shows engine-out PM levels, while the other shows CSF-out PM levels. These results are also shown in Table 2.

Figure 3. Effectiveness of a CSF in Reducing Total Particulate Mass.

Table 2. Engine and CSF Emission Data for EPA Transient Cycle Using a C8.3-275 HP Transit Bus Engine.

Emission	Total Particulate	Soluble Organic Fraction	Total Hydrocarbon	Carbon Monoxide
Engine-out (g/bhp-hr)	0.09	0.05	0.18	0.69
CSF-out (g/bhp-hr)	0.02	0.01	0.05	0.21
Reduction (%)	80	78	70	70

In addition to the New Jersey field-testing, Cummins also sponsored laboratory emission characterization studies for diesel engines equipped with CSFs. The ESTCP program indirectly provided partial funding for this investigation. This work was carried out at Michigan Technological University (MTU) and is described in references 1 and 2. The MTU results, over a certain range of engine operating conditions, indicated that in addition to a significant total mass reduction in particulate matter, a uniform reduction over most of the instrument's range of particle sizing was observed. Figure 4 shows the effect of CSF on particle size distribution.

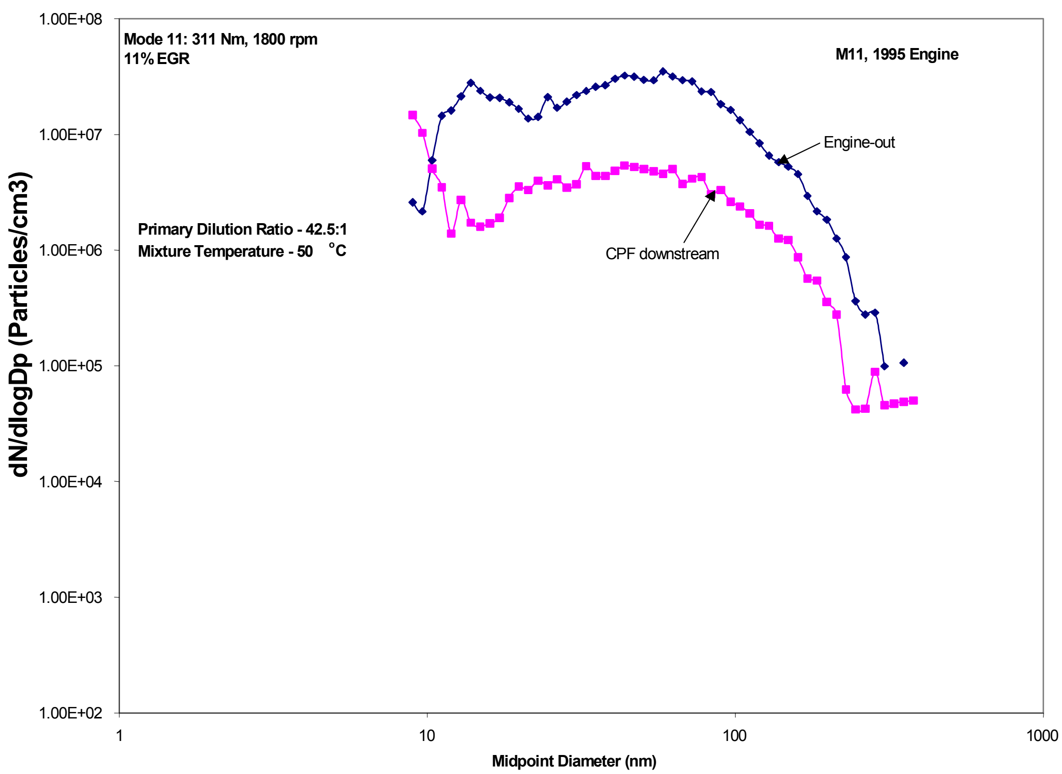

Figure 4. Normalized Particle Size Distribution with Little or No Particulate Combustion (MTU Study) [1].

Additional work at MTU focused on the effects of fuel sulfur on the emissions from an engine equipped with a CSF in the exhaust. Two fuels were used for the study: a conventional low sulfur fuel (CLSF), having a sulfur level of 375 ppm, and an ultra low sulfur fuel (ULSF), containing 0.57 ppm of sulfur. Two separate steady state engine conditions were tested: Mode 11 (25% load, rated speed) and Mode 9 (75% load, rated speed). Table 3 shows that the ULSF demonstrated greater total particulate matter (TPM) and solid particulate reduction, especially at Mode 9.

Table 3. Change in Emissions with a Catalyzed Filter for Fuels with Different Sulfur Levels.

	TPM	Solids	SOF	SO_4
Mode 11				
CLSF	-82%	-79%	-86%	-61%
ULSF	-88%	-80%	-93%	200%
Mode 9				
CLSF	-37%	-32%	-86%	531%
ULSF	-78%	-77%	-84%	337%

It is important to note the increase in sulfates produced with the soot filter installed. These particulates form as a result of the undesirable oxidation of sulfur dioxide (SO_2) over the catalyst, particularly at higher temperatures. As expected, at the high temperature mode 9, it is seen that the higher sulfur fuel produces significantly more sulfate. Although the sulfate increased by 200% and 337% for the ULSF, the magnitude of the sulfate levels were very low due to its lower sulfur content. The differences in the particulate emissions results between the two fuels are attributed to both sulfur levels and different hydrocarbon compositions between the two fuels. For instance, it was thought in the study that the solids were lower with the ULSF (aromatics 25.1%) compared to the CLSF (aromatics 34%), as previous studies have demonstrated that fuels with higher aromatic content produce greater particulate emissions.

Another interesting result of this MTU study was that despite higher filter inlet concentrations of solids using the CLSF, the pressure drop across the filter was higher with the ULSF. This can be seen in Figure 5.

With a greater amount of solids entering the filter for testing with CLSF, it would be expected that this would result in a greater soot thickness on the filter walls, creating higher pressure drop. However, it is believed that there may be differences in the characteristics of the soot between the two fuels, including particle size, penetration depth into the filter walls, packing density of the soot layer, and permeability of the soot.

With regard to testing of the Rypos system, the initial media testing was completed in-house at Rypos and was reported to be over 90% efficient in soot filtration efficiency. Subsequently, various filter geometries and exposed filter surface areas were tested until an optimum design was selected.

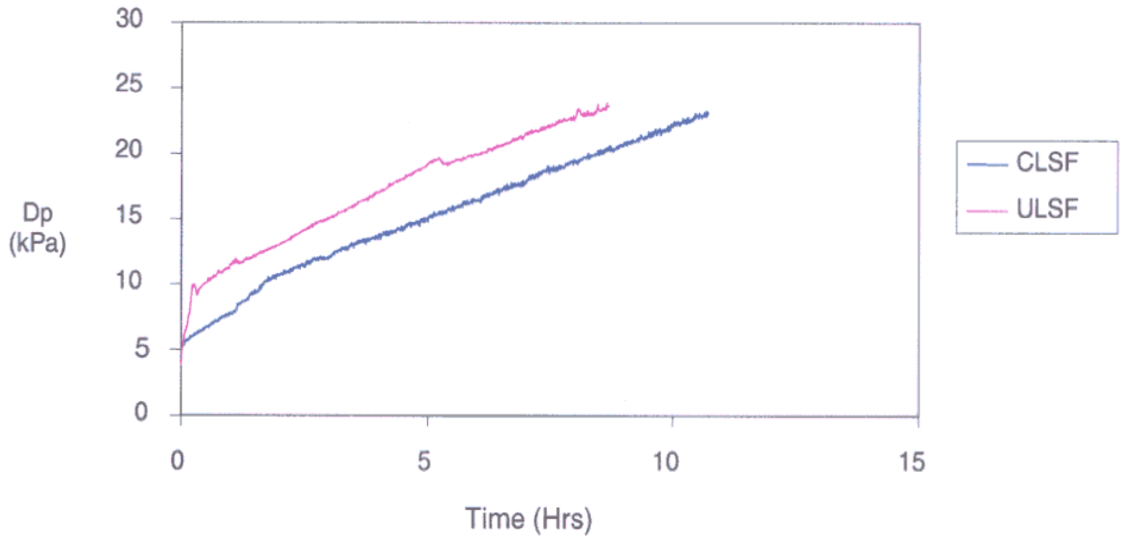

Figure 5. Pressure Drop Across Catalyzed Soot Filter Using Different Fuels.

Third party chassis dynamometer testing was completed at the emissions lab of Environment Canada. Filtration efficiencies as high as 85% were demonstrated. More recently, concurrent testing is being completed on three generator-sets. These gen-sets have ratings of 100 kW, 200 kW, and 400 kW. The results from this testing are forthcoming.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The primary reason for development of the soot filter and its main advantage is its effectiveness in reducing the total mass of particulate matter emitted from a vehicle. By trapping and combusting particulate matter, the total regulated exhaust emissions are significantly reduced. Throughout this process, no operator attention is required, thereby allowing normal vehicle or generator operation. In addition, the filter is effective in reducing noise and may replace the vehicle muffler.

As with all developing technologies, cost is a significant concern. Although there are a variety of advantages, catalyzed soot filters also exhibit several limitations. One limitation is the formation of solid sulfates over the platinum catalyst and the consequent reduction of filtration efficiency. With future reduction of fuel sulfur levels, this problem will be reduced. Another major setback for CSFs is that they are application duty cycle dependent. Some engines do not produce sufficiently high exhaust temperatures (i.e., >360°C) to initiate combustion of the trapped soot, resulting in filter plugging and possibly uncontrolled regeneration. As previously mentioned, uncontrolled regeneration occurs when the vehicle is operated at high loads, resulting in exhaust temperatures high enough to initiate soot combustion. If this is immediately followed by engine operation at low load (i.e., idle condition), there is not enough exhaust flow to carry away the heat. Therefore, the temperature in the filter rises rapidly, creating an exotherm. During such an occurrence, melting or cracking of the filter substrate is highly probable. When portions of the substrate are melted or if cracks are present, filtration efficiency decreases dramatically. Besides uncontrolled regeneration, ash plugging is also an associated concern and will necessitate periodic maintenance.

With regard to the Rypos system, the high exhaust temperature requirement of the CSF is not applicable since electricity is used to provide supplemental heat. The system does, however, have two disadvantages. One disadvantage is that because no catalyst coating is present, there is little,

if any, reduction of hydrocarbons and CO emissions. The other disadvantage is the increase in fuel penalty associated with parasitic power losses from the engine. Engine power will be required to drive a second or larger alternator or the electric generator for power generation applications.

In addition to the soot filter technology, several other competing technologies are being developed. Like soot filters, they have their advantages and limitations. A novel system that makes use of an uncatalyzed substrate is the Continuously Regenerating Trap (CRT) system developed by Johnson Matthey. An oxidation catalyst, upstream of the filter, generates nitrogen dioxide (NO_2). Depending on certain parameters, the NO_2 oxidizes the soot at temperatures as low as 277°C. A major limitation of this technology is that very low sulfur fuel (< 50 ppm) must be used in order to make the CRT perform effectively. Oxidation of SO_2 reduces the availability of platinum (Pt) sites for NO_2 formation, which could reduce the effectiveness of a CRT under current sulfur levels. In addition, the high precious metal loading of the oxidation catalyst can promote sulfate formation if conventional sulfur fuels are used.

Another alternative to catalyzed substrates is catalysts added to the fuel. This seems to be an effective system for reducing soot oxidation temperatures due to better contact between the catalyst and particulate matter. However, a number of concerns accompany this type of system, including the complexity and expense of additive dosing systems, possible premature wear of engine components, and increased additive ash.

3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

Table 4. Performance Objectives.

Type of Performance Objective	Primary Performance Criteria	Performance Objectives (Metric)		Actual Performance Objective Met?
		Expected	Targeted	
Quantitative	**Passive-CSF**			
	PM reduction 90% (minimum)	At least 2,000 EPA on-road standard 0.1 g/bhp-hr	Targeting 0.01 g/bhp-hr	Yes
	CO reduction 50% (minimum)	15.5 g/bhp-hr	Targeting 7.2 g/bhp-hr (ULEV clean fleet standard)	49% Minimum observed
	HC reduction 75% (minimum)	1.3 g/bhp-hr	Targeting 0.5 g/bhp-hr	72% Minimum observed
	Active-Rypos			
	PM reduction 90% (minimum)	At least 2,000 EPA on-road standard 0.1 g/bhp-hr	Targeting 0.01 g/bhp-hr	62% Average reduction
	Passive-CSF			
Qualitative	Maximum Backpressure of 6-10 inches Hg. at rated conditions	6-10 inches Hg of backpressure	Targeting an average of 8 inches Hg	Maximum backpressure recorded was 6.5 inches Hg
	Standard EPA on-road diesel fuel	500 ppm Sulfur	Targeting 320 EPA standard certified fuel	Highest observed was 428 ppm. Lowest was 203 ppm
	Service internal of 1,000 hrs or 50,000 miles	Filter reversals at 50,000 mile	Roughly once yearly	No service required during test. Maximum miles on single vehicle = 24,500
	Exhaust temperature 10% operation at >360°C	10% vehicle operation at >360°C	Targeting 10% operation at >360°C	75% of vehicles met requirement
	Active-Rypos			
	Maximum Backpressure of 6-10 inches Hg. at rated conditions	6-10 inches Hg of backpressure	Targeting an average of 8 inches Hg	Maximum backpressure recorded was 3.52 inches Hg
	Service internal of 1,000 hrs or 50,000 miles	Filter reversals at 50,000 mile	Roughly once yearly	No service required during test. Maximum engine hours = 87

Note: Emissions test results reported for the passive CSF filters were from the CARB emissions test facility. Tests on the Rypos filters were conducted by the University of Utah emissions testing team.

3.2 SELECTION OF TEST SITE/FACILITY

The first phase of the project was an exhaustive survey of diesel-powered vehicles and equipment at several military bases in Utah and southern California to identify applications for soot filters. Of the 85 applications examined, 20 were chosen as potential retrofit candidates based on probable duty cycle temperatures, the number of that type of application, engine age, amount of use and ease of filter installation. To ensure that these engines produced exhaust temperatures high enough to regenerate a passive soot filter successfully, each was temperature-logged during Phase 2 of the project. It was found that only 5 of the 20 engines exhibited sufficient exhaust temperatures for the catalyzed soot filters. These were buses and trucks located at Camp Pendleton, CA and Fort Irwin, CA. Therefore Camp Pendleton and Fort Irwin were selected as test sites. Due to the limited number of vehicles suitable for low precious metal catalyzed soot filters, active systems were also investigated. The Rypos units were selected, as previously described, and portable tactical diesel generators at Edwards Air Force Base (AFB) were chosen as optimal applications. Edwards AFB was chosen because of gen-set availability and close proximity to NFESC. The 20 applications that were data logged for duty cycle temperatures, plus the additional gen-sets at Edwards AFB, are included in Table 5. This table also shows the EPA air pollution attainment status at each DoD test location.

Table 5. Diesel Engines Evaluated during Phase 2.

Location	EPA Air Pollution Attainment Status	Engine Applications
Marine Corps Base, Camp Pendleton, CA	Non-Attainment Area	- 10 kW Generator - 40 Passenger Bus - 36 Passenger Bus
Army National Training Center, Fort Irwin, CA	Attainment Area	- 40 Passenger Bus - 36 Passenger Bus - Stake Truck - Heavy Equipment Transporter - Hemmitt Refueler - 110 kW Generator - HMMWV - Mod 2
Hill Air Force Base, Layton, UT	Attainment Area	- 72 kW Generator-Set - 15-Ton Crane - Aircraft Tow Vehicle
Ventura County Naval Base, Point Mugu Complex, Point Mugu, CA	Non-Attainment Area	- Aircraft Tow Tractor - Equipment Tow Vehicle - Man Lift
Navy Public Works Center, San Diego, CA	Non-Attainment Area	- Semi-Tractor - 80-Ton Winch Engine - 120-Ton Crane Winch Engine
Channel Island Air National Guard Base, Point Mugu, CA	Non-Attainment Area	- Aircraft Refueling Truck
Edwards Air Force Base, CA	Non-Attainment Area	- 72 kW Generator-Set

3.3 TEST SITE/FACILITIES HISTORY/CHARACTERISTICS

The diesel applications selected for soot filter installation in Phase 3 of the project were located at the following DoD facilities:

Marine Corps Base, Camp Pendleton, CA is the site of the Marine Corps' largest amphibious assault training facility, encompassing 125,000 acres and 17 miles of Southern California coastline. The base has a population of nearly 40,000 Marines and Sailors. As such, nearly all types of equipment in the Marine Corps inventory are located at this facility. As a functioning training command, the equipment is used almost daily for training and transportation purposes. The three buses selected for the demonstration are used to transport Marines to the widely separated training ranges within Camp Pendleton, and to other Marine Corps activities in southern California.

Army National Training Center, Fort Irwin, CA, covers approximately 642,000 acres and provides the Army with a realistic desert-training environment. Army field units from across the country routinely deploy to Fort Irwin for four-week periods to practice war tactics and hone their war fighting skills. The base is equipped with electronic firing ranges that can determine the outcome of simulated battlefield scenarios. Units deployed to the Training Center use standard issue Army equipment, drawn from an inventory of equipment that remains at the Training Center for use by visiting training units. The equipment has a high rate of usage, making them ideal candidates for CSF testing. The climate at Fort Irwin, very hot summer days, with cold winter nights, provided the ability to test the soot filter in a wide range of temperatures. The three buses selected for the demonstration are primarily used to transport employees to and from Barstow, CA. The stake trucks are used to transport materials in the Barstow area.

Edwards Air Force Base, CA, covers approximately 300,798 acres in the Mojave Desert of southern California. The base is the main Air Force facility that conducts and supports research, development, test, and evaluation of manned and unmanned aerospace systems. In performing this mission, the base utilizes a wide range of aircraft support equipment. Nearly all of this equipment is identical to that used at other Air Force installations in support of operational forces. Testing the tactical gen-sets at Edwards AFB provided information that is directly applicable to other Air Force installations worldwide. The climate of Edwards AFB, very hot summer days, with cold winter nights, provided the ability to test the soot filter in a wide range of temperatures.

3.4 PHYSICAL SET-UP AND OPERATION

Eight vehicles were chosen for CSF installation based on the preliminary temperature logging results described in Section 3.2. The field test of these vehicles ran from June 2001 to March 2002. During the demonstration, the vehicles operated under normal duty cycles.

Since one vehicle may be operated under different conditions (i.e., different routes) compared to the rest of a fleet, it would not be wise to assume that a soot filter does or does not function properly on that type of vehicle if only one is tested. Therefore, where possible, a duplicate vehicle was outfitted with a CSF. For instance, duplicate installations were performed on the stake truck at Fort Irwin and the Thomas buses at both Fort Irwin and Camp Pendleton. The Bluebird buses are limited in numbers, making them more difficult to pull out of service. Therefore, duplicate installations were not used.

The CSFs were designed and constructed by Nelson industries, a Cummins, Inc. subsidiary using catalyzed soot filter substrates provided by Engelhard. The catalyst canning duplicated the existing mounting, and inlet and outlet connections, thereby allowing simple replacement of the muffler. Project personnel, with assistance of civilian Marine Corps diesel mechanics, performed all the filter installations and removals.

Different catalyst loading amounts were implemented, based on the exhaust temperatures and fuel sulfur levels measured during a previous phase of the project. Lower temperature applications require higher catalyst levels. Table 6 details the vehicles, engines, filter sizing, and loadings.

Table 6. List of Applications Tested with a Catalyzed Soot Filter.

Vehicle	Vehicle Year	Engine	Catalyst Loading (g/cu. ft.)
Camp Pendleton			
Thomas Bus-00582	1999	CAT 3125, 330HP	5
Thomas Bus-00583	1999	CAT 3125, 330HP	5
Bluebird Bus-294509	1996	B5.9-190	10
Ft. Irwin			
Thomas Bus-00172	1998	ISB-230	5
Thomas Bus-00177	1998	ISB-230	5
Bluebird Bus-35898	1996	B5.9-230	10
Stake Truck-16431	1994	B5.9-190	10
Stake Truck-14719	1997	B5.9-175	10

Demonstration of the Rypos (Medway, MA) active soot filters was performed from March to July 2002. Two duplicate Air Force tactical gen-sets at Edwards AFB were chosen for the testing. These generators provided sufficient electrical input to the Rypos electrically regenerating soot filters so that no additional power source was necessary. The gen-sets were powered by Cummins B5.9 engines rated at 185 horsepower (model year 1998). To minimize the design costs for the demonstration, the existing muffler was replaced with exhaust piping and the soot filter was installed on top of the gen-set. Project personnel performed the installation.

Once the field-testing was completed, both the CSFs and active filters were removed and returned to Cummins and Rypos, respectfully, where they were visually inspected for failure. The original mufflers were then reinstalled on the engines.

3.5 SAMPLING/MONITORING PROCEDURES

Since testing was carried out in the field, the primary criteria for test method selection were the mobility and robustness of measurement equipment. Cummins personnel performed the data analysis.

During the entire demonstration phase, exhaust temperature and backpressure data were collected every 10 seconds to verify proper operation and to determine the effectiveness of the soot filter in actual field operation. A total of 8.1 million data points were collected over the entire field

evaluation. The data was acquired with a Campbell Scientific 21X data logger that was installed on the vehicles. Data was downloaded approximately once per month.

At the time of the data download, NFESC engineers reviewed the data to identify any thermocouple or pressure transducer failures. The data was also reviewed for consistency with previous data. This was accomplished to identify changes in engine use or potential maintenance problems. Exhaust temperature was measured at the inlet and outlet of the soot filter. The filter inlet temperature provided a means to determine whether or not the exhaust entering the filter was at a high enough temperature to oxidize the soot and regenerate the trap. For the passive CSFs, measuring the outlet temperature provided a way of determining if an exotherm had occurred in the filter due to uncontrolled regeneration, thereby providing a warning of potential filter substrate damage. The backpressure data gave an indication of the effectiveness of the self-regenerating characteristic of the CSF and served as an alarm for manual filter cleaning if the backpressure reached excessive levels. For the Rypos active soot filters, one additional parameter was recorded. A signal was acquired every time the filter began regeneration, thus affording a way to determine how often the filter was requiring power from the gen-set.

In addition to this regeneration performance data, multiple emissions tests were also performed on five engines. Traditional EPA approved (40 CFR 86.1301) and newly developed test methods were employed. The newly developed test methods are described in detail in paragraph 3.6 and the emissions testing results are provided in paragraph 4.1.

3.6 ANALYTICAL PROCEDURES

The original project plan was to only perform air emissions testing in the laboratory. This decision was made based on the difficulty of performing accurate field PM measurements. While the measurements of gaseous (i.e., CO, HC and NO_x) air emissions performed in accordance with 40 CFR 86.1301 are straightforward direct measurements of a representative gas sample using electronic meters, the measurement of PM requires the use of carefully controlled and measured dilution air. The EPA approved PM test method is a gravimetric analysis (collecting particulate matter on paper filters and then weighing them) performed using an air dilution tunnel. This standard method is used for both engine and filter certification. It does not; however, allow for real-time testing nor for the measurement of particle size distribution. Recently, the University of Utah, using Strategic Environmental Research and Development Program (SERDP) funding, has been evaluating rapid-response PM measurement methods for use in the field. The following paragraphs describe the methods used by the University of Utah to evaluate the soot filters.

Prior to performing their PM measurements, the University of Utah diluted the diesel exhaust with clean, filtered air. The dilution ratios ranged from 1:2.25 to 1:32.0 (sample: dilution air), and the ratios were selected to ensure that all instruments measured within their operating ranges.

The particle measurement instruments included a Scanning Mobility Particle Sizer (SMPS), an Optical Particle Counter (OPC), (LASAIR Corp. model 310), a Photoelectric Aerosol Sensor (PAS), (EchoChem Inc., model 2000), a Dust Track (DT), (TSI, Inc. model 8520), and a Photoacoustic Analyzer (PA), (Desert Research Institute). The SMPS provided particle size distributions for particles ranging from 14.6 to 661 nm. For the initial bus tests, the OPC provided particle counts for larger particle sizes. Specifically, it measured particle counts based on light scattering in seven size channels ranging from 0.3 µm to 10 µm, and recorded average particle concentrations every

minute. The OPC required additional dilution to keep it operating within its measurements limits, and the smallest particles detected are larger than the typical diesel exhaust particle. Therefore, the DT was selected for the follow-up bus tests and the generator tests. The DT recorded the mass of PM_{10} (particulate matter smaller than 10 um) (mg/m^3). This instrument did not require additional dilution, and it is more sensitive than the OPC to the smaller particles found in diesel exhaust.

In addition to particle mass and size distribution, the team measured particle-bound black carbon (i.e., soot), and polycyclic aromatic hydrocarbon (PAH) concentration. The Desert Research Institute photoacoustic analyzer detects and quantifies black carbon particles in real time, providing a measure of soot mass. The PAS measures particle-bound PAHs on a real-time basis.

Measurements were collected for at least 10 minutes to allow for stable, consistent readings. Bus measurements were taken at known engine loads using a chassis dynamometer, and generator measurements were taken using an electric resistance load bank. Testing was performed both before and after filter installation at three engine load conditions that simulated normal operating conditions.

For the bus testing, several different speed/load points on the dynamometer were evaluated; 50% and 25% load at 55 mph, and idle. The 55 mph speed was chosen because it was a common speed traveled by the buses. Since each bus operated at each condition for at least 10 minutes for exhaust sampling, the dynamometer load had to be limited to 50% to prevent the tires located on the dynamometer rollers from becoming hot and failing. For the Rypos gen-set testing, loads of approximately 28 kW and 54 kW (at constant 2000 rpm engine speed) were selected. These loads represent approximately 40% and 75% of full load, respectively, and provided a broad range over which to test the PM emissions. Loads were limited to 75% since if any higher loads were applied, the engine would derate in the middle of the University of Utah's sampling. The manufacturer of the generator was unsure why this occurred. Refer to the Final Report[3] for full descriptions of the methods used to evaluate the soot filters.

4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE DATA

Passive filters were successfully field tested on eight buses and trucks from June 2001 to March 2002. A total of 98,097 miles were accumulated with the traps installed. Individual vehicle mileage ranged from 1,037 to 24,483 miles. The amount of vehicle use, downtime and instrument failure showed the need to have multiple test vehicles to maximize the amount of data acquired.

Active filters were tested on two Force tactical diesel generators from March 2002 to July 2002. One gen-set accumulated 55 operating hours while the other had 87 hours. No test equipment failures occurred during the demonstration. Total operating hours were less than expected.

In general, for the passive soot filter demonstrations, the performance objectives listed in Table 4 were met with some small exceptions. The CO and HC emission reduction targets were not met for the NYBC test cycle test of the Camp Pendleton Thomas bus. The results were, however, very close to the target. In addition, not all the demonstration vehicles had an exhaust temperature at or above the filter regeneration temperature for 10% of their duty cycle. This was a particular problem for the white stake truck at Fort Irwin, which was never driven off the base during the demonstration, and was rarely subjected to high engine loading.

For the active soot filters, the primary performance criteria of reducing soot by 90% was not met. All the other criteria were met. Given the large number of demonstration engines and the high quantity of test data collected, it is not expected that the project's results would significantly change with the addition of more data.

The project performance results are broken down into four groups. The first set of results is from the CARB laboratory. The second set is from the field PM measurements taken by the University of Utah. The third set of results are the pressure and temperature data collected during the field test, and the fourth is filter inspection performed after the completion of the field test.

4.1.1 CARB Emissions Test

The Clean Air Vehicle Technology Center (CAVTC), a contractor operated CARB facility located in Los Angeles, California, conducted gravimetric chassis dynamometer testing on Thomas bus 00583 using the EPA approved (40 CFR 86.1301) test method to measure for CO, HC, NO_x and PM emissions. Testing was performed at the end of the field test in February 2002. Three separate transient cycles were used to evaluate the performance of the trap: the Central Business District (CBD), Urban Dynamometer Driving Schedule (UDDS), and New York Bus Cycle (NYBC). Test cycles were run with the filter installed, and then again with the original exhaust configuration. Filtration performance and change in gaseous emissions are shown in Table 7.

Table 7. Change in Emissions and Fuel Economy with CSF Installed.

	Test Cycle	PM g/mile	THC g/mile	CO g/mile	NO_x g/mile	NO_2 g/mile	CO_2 g/mile	F.E. mpg
OEM Configuration	CBC	0.361	0.669	4.240	12.55	0.965	1674.3	6.0
	NYBC	1.514	1.165	17.463	29.61	2.281	4024.1	2.5
	USSD	0.314	0.316	3.713	9.23	0.610	1238.2	8.2
Engines with CSF Installed	CBD	0.015	0.075	0.357	12.25	1.013	1792.7	5.7
	NYBC	0.024	0.329	8.910	38.75	2.177	3905.5	2.6
	UDDS	0.017	0.069	0.703	10.21	0.801	1242.1	8.2
% Reduction From OEM Configuration	CBD	-96.0%	-88.8%	-91.6%	-2.4%	5.1%	7.1%	-6.0%
	NYBC	-98.4%	-71.8%	-49.0%	30.8%	-4.6%	-2.9%	3.5%
	UDDS	-94.7%	-78.3%	-81.1%	10.6%	31.4%	0.3%	0.1%

After seven months of field-testing, it can be seen that the filtration efficiencies remained high. The lowest PM efficiency was 94.7% for the UDDS, the most aggressive driving cycle. Substantial reductions of total hydrocarbons were also observed, the lowest being 71.8% for the NYBC cycle. Carbon monoxide and NO_x reductions varied significantly from cycle to cycle. CAVTC personnel observed greater than average test-to-test deviations in the NO_x measurements during the testing, but were not able to ascertain why. Overall, the higher NO_x values are unexpected since, with the filter installed, it is expected that the backpressure would cause an increase in in-cylinder residual exhaust gases, thereby contributing to lower engine-out NO_x emissions. The fuel economy, in miles per gallon, was determined by performing a carbon balance. A slight decrease in fuel economy is expected with a soot filter installed due to the added backpressure. Measurement errors and cycle-to-cycle driving variability could account for variation in the results.

4.1.2 University of Utah Field PM Testing Results

The team from the University of Utah was also present during the CARB tests in order to sample exhaust during the transient cycles. The results are shown in Table 8.

Table 8. Emission Reduction for Thomas Bus 583 during Transient Cycle Testing.

Driving Cycle	DT (% Reduction)	Test Instrument PA (% Reduction)	PAH (% Reduction)
CBD	98.2	96.0	98.5
NYBC	99.3	99.2	98.4
UDDS	99.0	99.7	98.5

As Table 8 indicates, the filtration efficiencies are high and relatively close to the CARB results. The University of Utah results did, however, show consistently higher emission reductions. One explanation for this is the large impact of the small number of very large exhaust particles emitted from diesel exhaust. These particles are typically composed of rust from the exhaust system or conglomerates of soot particles. Their effect on the testing results is much greater when testing a CSF-equipped engine since the overall PM emissions are much lower. During the testing, the University of Utah drew their exhaust sample through a 0.5-inch tube inserted into the 6-inch CARB

sampling pipeline connected to the bus's exhaust. Although the University of Utah minimized bends in the tubing and the length of the tubing prior to dilution, it is possible that the larger particles would adhere to the walls of the sampling tube prior to reaching the test instruments. This would reduce the particles seen by the instruments and thus explain the higher reported removal efficiency.

Besides testing the transient cycles for Thomas Bus 00583, the University of Utah team also measured PM emissions at steady-state engine conditions for all three of the demonstration buses located at Camp Pendleton, and for the two tactical generators located at Edwards AFB. The results are summarized in Table 9. Camp Pendleton testing was performed in June 2001 before the passive soot filter were installed and immediately afterwards, as well. It was repeated at the end of the demonstration in February 2002 both with and without filter installed. The second round of testing was used to determine if filtration efficiency changed during field test. Since two Thomas buses were tested, they are identified by their GSA license plate number. The Edwards AFB emissions testing occurred in July 2002 at the conclusion of the field-testing. It included emissions measurements taken before and after the filters were removed.

Table 9 shows that the passive filters generally removed 90 to 95% of PM. One exception to this is OPC results, which varied more than the other measures. This is not unexpected because OPC measures particles larger than typical diesel particles. For the buses, the removal efficiencies from PA, PAS, and SMPS tended to be similar and higher than that from the DT. This may be due to the fact that black carbon and particle-bound PAHs tend to be associated more with particles in the size range measured by the SMPS. Of note is that Table 9 does not contain SMPS data for the initial bus tests. Unfortunately, a computer crash caused the SMPS scans to be lost. An interesting conclusion from the CSF data is that the measured filtration efficiencies were approximately the same after the 8-month field test, indicating that the filters sustained real-world conditions while still performing just as well as when new.

In contrast to the passive filters, the active filters appeared to be less efficient at removing PM, with removal efficiencies averaging 62%. Upon post-test inspection of the Rypos traps, it was found that gaskets between the filter cartridges on the units had failed, allowing soot to pass. In addition, there was evidence of soot leakage through the filter media on one of the cartridges. Lower than expected filtration efficiencies during the University of Utah test is attributed to these findings. Additional details of the trap post-test inspections are presented in Section 4.1.4.

During the June 2001 test of the newly installed filter on the Bluebird bus, multiple SMPS scans of particle size distributions were acquired. Figure 6 shows the decrease in particle number across nearly all sizes as consecutive scans were taken from 0 to 18 minutes. This is expected as the filtration efficiency of a soot filter increases after a cake of soot forms on the monolith wall and acts as a filtration mechanism itself. This phenomena serves as a reminder to "de-green" a soot filter before emissions test are performed. Following this discovery, buses with newly installed traps were allowed to idle as long as possible (at least 30 minutes) before testing to minimize the degreening effect. Increased loads were not applied to increase the soot accumulation since tire wear and failure were an issue. Once partially degreened, the filters were tested at the previously described speed/ load points.

Table 9. Comparison of PM Removal Efficiencies.

Condition (load/rpm)	Percent Removal After Installation				Percent Removal After Use			
	PAS	PA	OPC	SMPS	PAS	PA	DT	SMPS
Thomas Bus 582								
Idle/800	99.1	98.9	84.9	--	99.9	99.8	92.3	97.0
25%/2,000	96.6	98.1	93.4	--	99.9	99.9	89.6	93.0
50%/2,000	96.2	97.5	97.9	--	99.8	99.8	90.3	90.5
Thomas Bus 583								
Idle/800	96.9	99.5	98.2	--	99.9	99.5	90.2	96.3
25%/2,000	99.1	98.9	78.0	99.2	99.9	99.8	92.0	97.3
50%/2,000	99.5	99.5	80.2	90.7	99.9	99.7	90.8	98.6
Bluebird Bus								
Idle/550	87.4	92.3	94.1	--	99.7	199	93.1	99.0
25%/55 mph	97.3	100	96.9	--	98.8	99.9	98.9	90.9
50%/55 mph	83.2	86.1	29.0	--	95.5	98.9	97.9	96.2
Tactical Generator DX02								
Idle/2,000	--	--	--	--	40.3	42.0	56.0	59.0
40%/2,000	--	--	--	--	51.1	56.9	65.2	46.3
75%/2,000	--	--	--	--	49.9	58.2	66.8	44.2
Tactical Generator DX04								
Idle/2,000	--	--	--	--	31.3	36.9	53.2	65.0
40%/2,000	--	--	--	--	52.1	59.3	68.6	67.0
75%/2,000	--	--	--	--	52.3	58.1	62.6	46.9

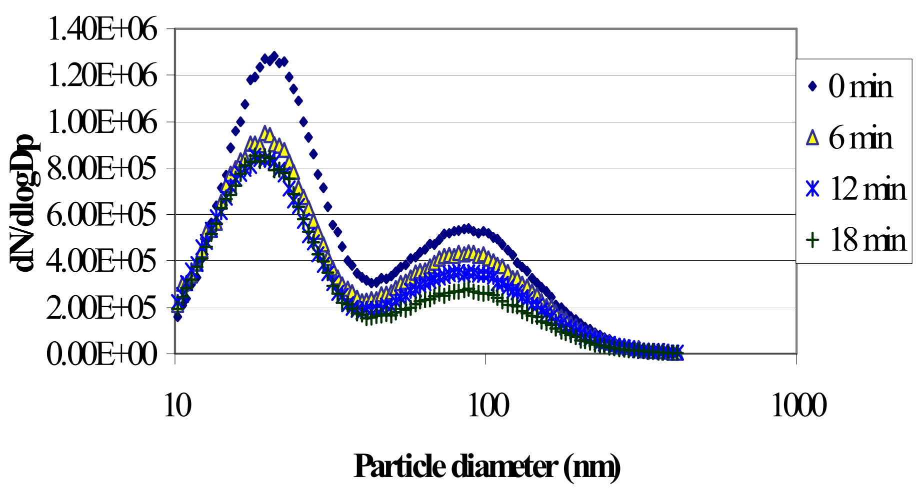

Figure 6. Soot Filter Degreening.

4.1.3 Exhaust System Temperature and Backpressure Measurement Results

At Cummins, the pressure and temperature data was segmented and analyzed in data sets ranging from 3 to 77 engine operating hours. The data was analyzed using a Matlab program that calculated the maximum recorded backpressure, and calculated the 10% temperature. This is the temperature of the engine exhaust that is met or exceeded 10% of the operating hours within the analyzed time interval. Previous studies have shown that low precious metal catalyzed soot filters require 10% temperatures of approximately 360°C. For the most part, looking at peak backpressures over a period of time indicates whether the trap is loading up with soot or is burning it. Increasing pressure shows soot or ash accumulating in the trap, whereas decreasing peak pressures indicates soot oxidation. This is not the most accurate method of determining regeneration performance since backpressure is a function of exhaust flow rate as well, and therefore all peak backpressures may not necessarily be at the exact same engine operating condition. However, at this time, it is the best tool available for this data. A plot of peak backpressures for the 5g/ft^3 catalyst loaded filters over the number of operating miles is given in Figure 7.

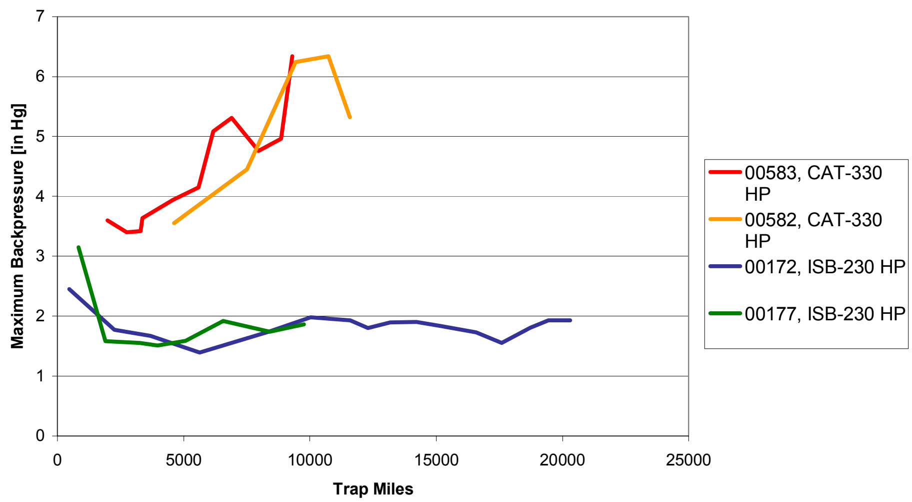

Figure 7. Backpressure Trends of 5 g/cu. ft. Filters.

The plot shows that Thomas buses 00583 and 00582 at Camp Pendleton exhibited increasing backpressure trends over the length of the test, whereas, Thomas buses 00172 and 00177 at Fort Irwin displayed a classic initial drop in pressure (thought to be related to a loss of washcoated catalyst), and then stabilized just under 2 inches Hg for the remainder of the test. These different trends are surprising. Buses at both locations have aggressive driving cycles and therefore high exhaust temperatures. The Fort Irwin buses are used to transport civilian and military passengers between communities around Barstow, CA and the fort. These routes are more than 30 miles in one direction, and include stretches of road over mountain passes at speeds of 55 mph. The Camp Pendleton buses also accumulate the majority of the mileage on-highway as well, traveling between the base and San Diego or for training exercises at the 29 Palms Marine Corps Air Ground Combat Center.

Figure 8 is a plot of the 10% temperatures for each of the buses during the field evaluation, which demonstrates that overall, the Camp Pendleton buses only showed slightly lower exhaust temperatures. One thing to note in Figure 8 is the decrease in exhaust temperatures to 353°C on Thomas bus 00583 at the end of the trial. This last portion of data was recorded during emissions tests when operating conditions were not as challenging as during the usual duty cycle. The average 10% temperatures for Thomas buses 00583 and 00582 were 411°C and 422°C, respectively, whereas the averages for Thomas buses 00177 and 00172 were 431°C and 432°C. However, this small temperature difference between Camp Pendleton and Fort Irwin buses is not expected to have caused the widely different pressure trend seen in Figure 7.

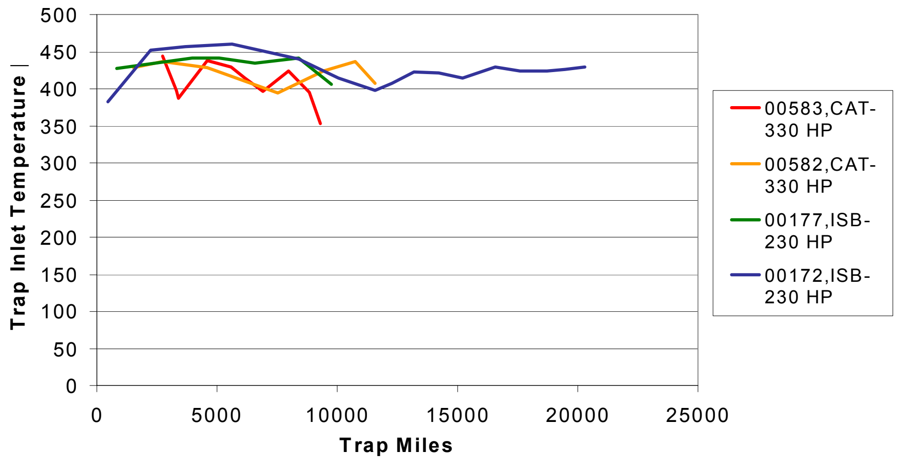

Figure 8. 10% Temperatures for 5 g/cu. ft. Filters.

Technical experts at Cummins have speculated that the observed backpressure differences between the Thomas buses can be attributed to engine-out particulate levels. While both were manufactured after 1998 and are EPA heavy duty certified, the Fort Irwin buses have Cummins engines while the Camp Pendleton buses have CAT® engines. There may be differences in the levels of soot or lube-oil ash each engine emits. In previous in-house testing at Cummins, particulate engine-out levels were lower on the ISB Cummins engine compared to a Detroit Diesel Series-30 engine and, as a result, the ISB produced lower and more stable backpressures at equivalent exhaust temperatures. It is thought to be the same case for this testing. The Fort Irwin ISB engines may output lower levels of soot or ash and therefore the traps remain cleaner.

Differences in particulate levels out of the engine can also be a reason why the filter on the Fort Irwin Bluebird bus, which runs the same routes as the Fort Irwin Thomas buses, continued to load up with particulate throughout the test. The peak backpressure plot for the Bluebird bus, along with the other vehicles with 10-gram traps, can be seen in Figure 9.

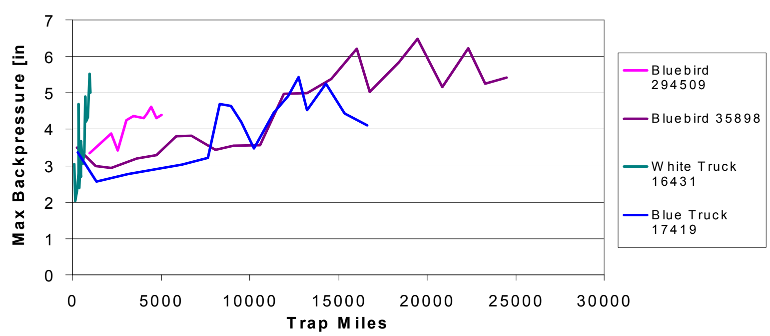

Figure 9. Backpressure Trends of 10 g/cu. ft. Filters.

Figure 9 shows that the maximum pressures for the Fort Irwin Bluebird bus increased over the first 15,000 miles and then fluctuated about 5.75 inches Hg. What is surprising is that the 10% temperatures were, for the most part, above 400°C, as seen in Figure 10.

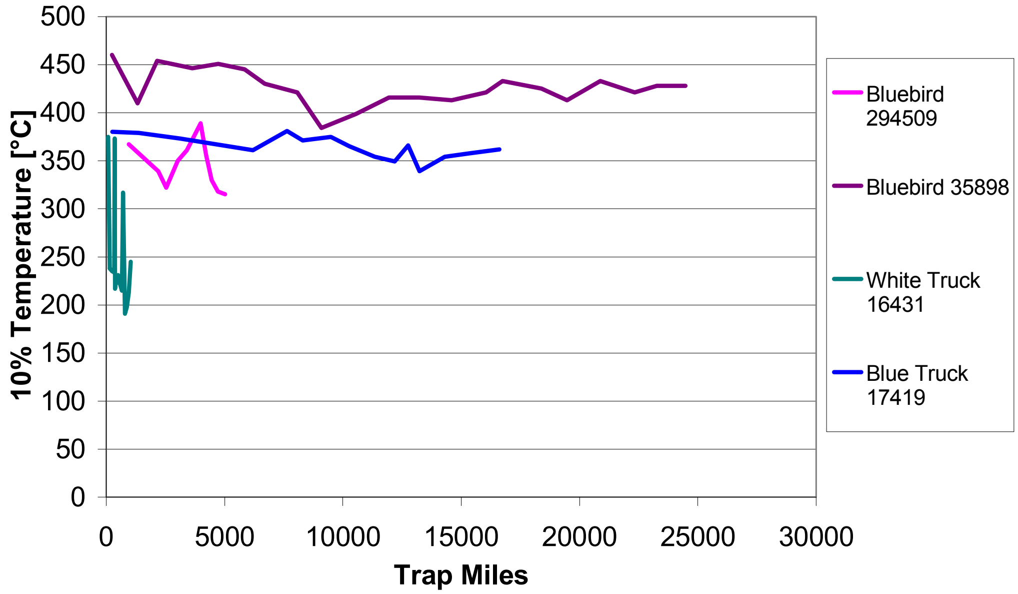

Figure 10. Regeneration Temperatures for 10 g/cu. ft. Filters.

The overall 10% temperature for Bluebird bus 35898 was 424°C, almost equivalent to the Thomas buses at Fort Irwin. Therefore, with twice as much precious metal, it would be expected that the Bluebird bus would have better regeneration performance than the Thomas buses. This again leads to the previously mentioned hypothesis; the two distinct pressure trends are thought to be due to engine-out particulate levels. The Bluebird bus is powered by a mechanical B5.9 engine, whereas the Thomas buses are driven by electronic ISB engines that afford more particulate control through variable injection timing.

As for the other three 10 gram filters, Figure 10 shows that the white stake truck and Bluebird bus 294509 had duty cycle temperatures that were not high enough for satisfactory regeneration performance, and therefore, the filters accumulated high amounts of soot, as seen in Figure 9. The white stake truck idled for up to an hour in the morning and rarely traveled off base. It was mostly used for small tasks at Fort Irwin, such as deliveries or garbage pick-up. Bluebird bus 294509 at Camp Pendleton similarly remained on the base, transporting Marines to various training grounds. The blue stake truck is a different case, as it was typically driven from the Dagget airport near Barstow up to Fort Irwin, a route similar to that of the Thomas buses. However, 10% temperature was marginal at 365°C. What also could have contributed to its high soot loading (see Figure 9) is the fact that it has a mechanically controlled engine.

Although a majority of the vehicles exhibited high soot loadings, no exotherms were seen in the filter outlet temperature data, indicating that no uncontrolled regenerations took place. A conclusion to be drawn from this testing and observation of the regeneration performance is that the 10% temperature rule is not applicable in all cases. Engine-out particulate levels influence regeneration performance to a greater extent than initially thought, and therefore, new tools have to be developed to determine whether or not an application can successfully regenerate a filter of a specified catalyst loading.

Active particulate traps have the advantage over catalyzed soot filters in that successful regeneration does not depend on exhaust temperatures. As is the case with Rypos systems, regeneration is

triggered based on the measured backpressure. This strategy prevents the backpressure from getting very high. Such was the case during the field test of the Rypos units in this investigation. Peak backpressures remained low throughout the test as can be seen in Table 10.

Table 10. Backpressures for Rypos Filters.

Gen-Set	Cumulative Running Hours	Peak Backpressure Observed During Test [inches Hg]
DX-02	87	3.26
DX-04	55	2.96[1]

Note (1): This maximum occurred while connected to a load bank

One thing to note is the low number of hours of operation that occurred over the field evaluation. The low usage was due to limited flight operations during the demonstration period. Table 10 shows that the backpressure did not exceed 3.26 inches Hg for gen-set DX-02 and 2.96 inches Hg for DX-04 during normal operation. Typically, regeneration of a cartridge occurred at least every eight minutes. Regeneration may have occurred more often than absolutely necessary since very small, if any, increases in backpressure were observed between the regenerations. Therefore, the system appeared to be over designed for the application. However, this was not unwise given that the duty cycles of the gen-set were unknown prior to the test. Due to such aggressive regeneration, the filters did not develop a cake of soot. This soot would act as a filtration mechanism similar to that experienced by a CSF. In this project, the active filters were not afforded this benefit. Optimization of the regeneration timing will result in improved filtration and energy efficiency.

4.1.4 Post-Use Filter Inspection Results

Following the completion of the passive filter field demonstrations (8 months at Camp Pendleton, and nine months at Fort Irwin), the passive filters were returned to the Cummins Technical Center in Columbus, Indiana, where the ends of the filter cans were cut off and the substrate faces inspected. During the inspection, no face plugging was observed on the inlet side, and cell openings did not appear diminished in size due to excess soot loading. However, on the outlet side of 4 of the 8 filters, soot deposition was observed at the periphery of the substrate, near the metal mesh gasketing. On all four of the damaged filters, the soot appeared 1 to 1.5 inches length around the circumference. The can around one of the substrates was cut off to inspect the substrate more closely. It was found that there was edge chipping and stress fractures approximately 1.25 inches long and about 0.25 inches in from the edge of the catalyst substrate. There was enough damage of the cells that soot escaped through the substrate and into the metal gasketing or on the can wall located directly downstream. This damage is shown in Figure 11.

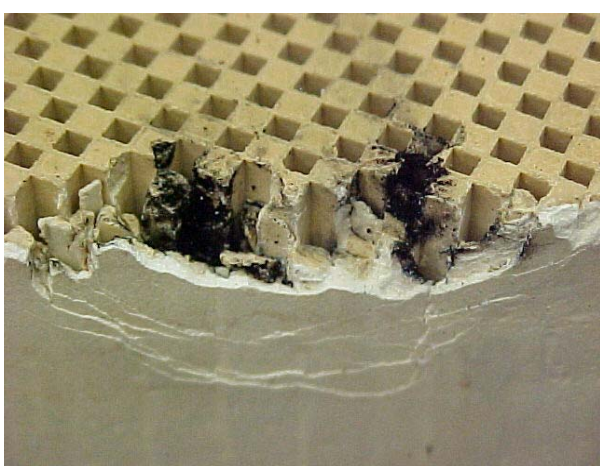

Figure 11. Edge Chipping of Substrate.

The filter shown in the Figure 11 happened to be from the bus that was emissions tested by CARB, and despite this damage, produced filtration efficiencies of greater than 94% for the tested cycles. This damage is likely caused by stresses placed on the substrate by the metal gasketing holding the catalyst substrate in place in the can.

As mentioned previously, post-test inspection of the Rypos traps revealed soot leakage problems with one of the filter cartridges and approximately 30% of the gaskets placed between the cartridges. One of the leaking gaskets is shown below in Figure 12 along with one that functioned as expected.

From the inspection of the gaskets, it was concluded that the gasketing material chosen does not appear to be resilient enough for this environment. It was further concluded that the gasketed subassemblies were somewhat misaligned. Development is on-going to prevent such leakage from occurring on future units.

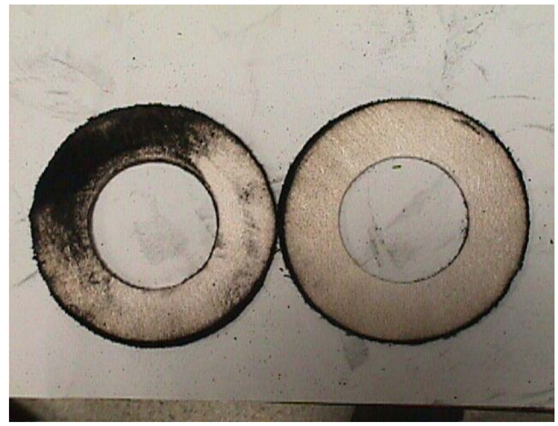

Figure 12. Rypos Filter Cartridge Gaskets.

4.2 PERFORMANCE CRITERIA

In general, the performance criteria were met (see Table 11). An exception was the soot reduction for the active filter. Qualitative criteria such as drivability and service interval were evaluated by discussion with site personnel associated with the vehicles or gen-sets. Regeneration performance was determined by examining the backpressure and temperature data collected during the field test, as described in earlier sections of the report.

4.3 DATA ASSESSMENT

For all the demonstration engines, no decreases in engine performance were observed, nor were any engine operator actions required. The catalyzed soot filters performed as expected with respect to particulate filtration performance. Even after being subjected to field test conditions, the filters performed up to the criteria standard and manufacturer claims (>90% particulate reduction).

The primary performance goal for this project was to reduce PM emissions by 90%, as measured for the same engine with the existing exhaust configuration. This goal was met for the passive traps and was not met by the active trap tested. Other goals, including reducing CO and HC emissions, maximum exhaust backpressures and adequate exhaust temperatures, were generally met. For the passive filters, most of the test vehicles experienced continuously increasing backpressures. Although the engine backpressure limits were not exceeded, the trend was not very good. This suggests that the potential market for low precious metal passive filters only represents a small portion, probably less than 25%, of the total diesel engines operated by either DoD or commercial interests.

The active electrical traps performed well with respect to backpressure; however, filtration efficiency remained lower than the performance criteria during the emissions testing.

Table 11. Expected Performance and Performance Confirmation Methods.

Performance Criteria	Expected Performance (pre demo)	Performance Confirmation Method	Actual (post demo)
Primary Performance Criteria (Qualitative)			
Regeneration	Controlled	Evidence of failure (i.e., substrate melting, large decrease in ΔP)	No evidence of uncontrolled regeneration
Service Interval	CSF reversal @ 50,000 miles	Recording of servicing details	No filters had to be serviced during test. Every vehicle accumulated less than 50,000 miles
Primary Performance Criteria (Quantitative)			
PM Reduction	PM Reduction 90% (minimum)	Photoacoustic Analysis, Smoke Test	Catalyzed traps: greater than 90% reduction Active electrical traps: average reduction of 62%
Backpressure	6-10 inches Hg maximum	Pressure Transducer	Catalyzed: Maximum backpressure recorded was <6.5 inches Hg Active electrical: Maximum backpressure recorded was 3.52 inches Hg
Secondary Performance Criteria (Qualitative)			
Drivability	No change	Driver response	No complaints from drivers about drivability

With respect to measuring particulate emissions, the University of Utah and CARB use different techniques; however, their data correlated relatively well. The two different sources of data with similar conclusions provided greater certainty of the filtration performance of the CSFs.

4.4 TECHNOLOGY COMPARISON

There are a very limited number of innovative particulate reduction technologies that can be implemented for the applications of interest in this study. One technology, the Diesel Oxidation Catalyst (DOC), has been shown to reduce particulate matter up to a maximum of only 50%. However, the reduction is mainly of the soluble organic fraction of the particulate. DOCs have very limited effectiveness on reducing the solid, carbonaceous particulate matter and, therefore, are less advantageous for the newer engines in this investigation that emit little Soluble Organic Fraction (SOF). Other technologies, such as the Continuously Regenerating Technology or a highly-loaded precious metal CSF require the use of ultra-low sulfur fuel so that sulfates are not produced. Currently, ULSF is not widely used at DoD facilities, and therefore, these technologies do not represent attractive alternatives at the present time.

5.0 COST ASSESSMENT

5.1 COST REPORTING

It is expected that the soot filter technologies demonstrated by this project will be suitable for a number of types and sizes of DoD diesel engines. Costs for implementation are expected to vary significantly for each proposed installation. It is, however, expected that site-specific issues will not significantly affect implementation costs.

The capital costs for the soot filter technologies are dependent on the size and use of the engine and the number of similar engines modified. The size of the soot filter increases with the size and load on the engine. As would be expected, bigger filters are more costly. Since soot filter systems must be custom designed and manufactured for each application, and since this is a significant portion of the total costs, the cost per filter significantly depends on the number of similar units manufactured.

Installation costs will likewise be dependent on the size of the engine and the number of engines to be modified. A more important factor, however, will be the actual placement of the filter. Applications with small engine compartments or torturous engine exhaust flow paths will be more expensive.

Annual soot filter operating costs are expected to be very low. Increases in fuel consumption are expected to be minimal. There are no actions required by the engine's operator. Expected filter maintenance consists of only of an annual cleaning. Since no cleanings were required during the demonstration, its cost will be estimated. The filters do not have any replacement parts nor do they have any requirements for consumables. Since at this time, implementation of PM reduction after-treatment technology on existing DoD engines is not a compliance issue, there are no additional direct or indirect compliance costs such as permitting for the implementing organization.

Filter disposal costs are expected to be minimal. Passive filters may, in fact, have some value since they contain a precious metal.

In order to provide meaningful implementation cost information, costs for two sample implementations will be shown. The actual costs experienced during the demonstration will not be reported. During the demonstration, prototype filters were used, while significant emissions testing, exhaust temperature, and pressure data were collected. All together, the unique demonstration costs were much higher than would be expected for future installations.

In Table 12, the costs per vehicle are reported for an installation of a passive soot filter on a post 1994 model year bus with a Cummins, 5.9-liter diesel engine that is expected to be driven approximately 15,000 miles per year. The installation of an active filter on a 72 KW Air Force tactical diesel generator is estimated to operate approximately 250 hours per year. These potential applications were chosen since they were included in the project's demonstration, and they are under consideration for future installations. The annual engine use estimates are based on averages experienced during the demonstration. For the purpose of this presentation, it will be assumed that the engineering associated with the sizing of the filters and the installation will be spread over 12 units, therefore, 8.33% of these costs will be added to the purchase costs. Installation and maintenance costs are based on a labor rate of $100 per hour. Since currently, no diesel exhaust

after-treatment is required, the cost for the existing process is $0 and, therefore, it is not shown in Table 12.

Table 12.   Types of Costs by Category.

(Bus With 5.9 Liter Cummins Engine)

Direct Environmental Activity Process Costs				**Indirect Environmental Activity Costs**		**Other Costs**	
Start-Up		**Operation & Maintenance**					
Activity	$	Activity	$	Activity	$	Activity	$
Equipment Purchase	$6,250	Yearly Cleaning	$300	None	--	None	--
Installation	$800			None	--	None	–

(Air Force 72 KW Diesel Generator)

Direct Environmental Activity Process Costs				**Indirect Environmental Activity Costs**		**Other Costs**	
Start-Up		**Operation & Maintenance**					
Activity	$	Activity	$	Activity	$	Activity	$
Equipment Purchase	$8,500	Biannual Cleaning and Inspection	$400	None	--	None	--
Installation	$1,000			None	--	None	--

5.2 COST ANALYSIS

The Net Present Value (i.e., life cycle cost) and the Net Annual Cost (i.e. annual life cycle cost) for the two sample installations, described in paragraph 5.1, is shown below. In order to perform the calculations, a 5% interest rate is assumed with a salvage value of $0, and the economic life of the soot filters are five years for the passive filter and 12 years for the active filter. These economic lives have been estimated based on the expected annual equipment usage and the filter lives estimated by their suppliers. Previous laboratory testing has shown that the filter's economic life is much more a function of its hours of operation verses its age.

Life Cycle Cost For Bus Passive Filter (5 years): $ 8,349
Annual Cost For Bus Passive Filter: $ 1,929

Life Cycle Cost For Air Force 72 KW Diesel Generator (12 years): $13,045
Annual Cost For Air Force 72 KW Diesel Generator Active Filter: $ 1,472

A careful analysis of life cycle costs shows that most of the costs are associated with the initial purchase price and installation costs (i.e., fixed costs). Only 15% (active filter) to 27% (passive filter) of the costs are associated with the operating costs (i.e., variable costs). Since the fixed costs are known, it is estimated that the total costs for the sample installations are accurate to within

+15%. Based on an estimated purchase cost of $7,000 for a Cummins 5.9-liter diesel engine, the passive filter purchase costs 89% of the engine costs while the active filter costs 121%.

Unfortunately, for other potential applications that were not included in the demonstration, the uncertainty of total life cycle costs is much higher. The total life cycle costs should, however, be similar since the two sample engines represent a good average size for diesel engines found at DoD facilities. The costs for implementing the soot filter technologies throughout DoD are likewise very uncertain. Although the number of heavy-duty diesel engines can be reasonably estimated, the number of engines that customers would be interested in modifying is not known. This number will greatly depend on future diesel engine retrofit regulations.

5.3 COST COMPARISON

Since the purpose of this ESTCP compliance project is to meet proposed future diesel engine PM emissions requirements, all costs associated with the development and implementation of the soot filter technologies represent new additional costs. Currently, no exhaust after-treatment technology is required to meet existing EPA regulations. Unfortunately, this will not true for the proposed 2007 heavy-duty diesel truck engine PM emission regulations nor for proposed retrofit programs.

In addition to the demonstrated soot filter technologies, other new innovative technologies have been suggested to reduce diesel engine PM emissions. Like soot filters, these technologies are in the initial development stages, therefore, little in the way of cost and performance information is available. An additional issue with some of these technologies is the fact that they require the use of ultra low sulfur fuel (<15 ppm). Unfortunately, this fuel is not universally available and therefore is not suitable for many military applications.

When comparing the measurable costs of the soot filter technologies, two indirect benefits need to be considered. Exposure to diesel engine particulate emissions has been identified as a possible human health risk. Since the purpose of this project is to significantly reduce PM emissions, it could be expected that DoD employee health care costs may be reduced as a result of the widespread implementation of this technology. Additionally, the reduction of PM emissions should provide a public relations benefit. The amount of smoke released from DoD vehicles operated on public highways will be reduced as a result of implementing this technology. This should improve the public perception of DoD.

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6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

There were many factors that significantly affected the final cost of this project. The primary factors were the extent of laboratory testing, the number of field screened engines, the number of demonstration engines, the number of test sites, the length of the demonstrations, the extent of emissions testing, and the number of demonstration technologies. Unfortunately, the financial control system used to account for the project costs was not of sufficient sophistication in order to associate project costs with these cost factors.

Overall, the project was completed within the originally approved budget. This performance was achieved even with a significant increase in the scope of the project. The reason that the additional work could be added without any additional costs was due to the nearly free emissions testing performed by the University of Utah (SERDP funded) and by CARB. In addition, the project's industrial partner, Cummins, contributed more resources than originally committed. Some of the significant project additions are listed below:

1. Performed 1,100 hours of soot filter testing at the Cummins engine test cell facility. The original Phase II target was 120 hours.

2. Provided financial backing for two Master theses at Michigan Technological University. This effort provided a characterization of PM emissions from a soot filter equipped diesel engine. It was not included in the original scope of the project.

3. Performed an initial field screening of 22 engines. The original goal was to measure exhaust profiles in the field on 10 engines.

4. Demonstrated passive soot filters on 8 engines. The original Phase IV goal was 5-6. In addition, the demonstration period was increased by two months.

5. Added vehicle emissions testing of the demonstration engines. Originally, only laboratory testing was to be performed.

6. Added the demonstration of two active soot filters. Originally, only passive filters were to be demonstrated.

For future installations, a significant reduction in costs is expected. During this project, the project team monitored filter performance on a monthly basis. This will not be done in the future. Also, the filters used were prototypes. As the market for soot filters develops, it is expected that their costs will decrease significantly and the engineering efforts required for installation will be reduced. At this point, the project team is only aware of one other potential hardware supplier. Since this potential supplier obtains their components from the same sources, it is not expected that they will be able to offer significantly lower prices.

6.2 PERFORMANCE OBSERVATIONS

Passive filters are only suitable for a limited number of potential applications. It is recommended that prior to implementing the passive filter technology, the fleet operator have representative engines field-screened to ensure that they have a sufficient exhaust temperature profile. The passive technology will fail without high enough exhaust temperatures. The failure mode could lead to a decrease in power, or to engine damage. Passive filters should only be installed on newer engines. It was found that on-road vehicles sold prior to 1994 have PM emissions that are too high for the filters to properly operate.

For the passive filters, the filter canning technique is important in ensuring filter substrate durability. As was discussed earlier in the report, edge chipping was observed where the filter comes in contact with its canning. This observation was made when several of the filters were destructively analyzed after the demonstration. New canning techniques have been developed to prevent such damage from occurring in future installations.

6.3 SCALE-UP ISSUES

For this project, full sized engines commonly found at DoD facilities were used for the demonstration. For future installations, it is expected that similar types of engines with similar duty cycles will be used. Scale-up should therefore, only involve placing soot filters on a larger number of engines. As will be discussed in paragraph 6.5, it is important to make sure that for any new application of a passive filter, the engine has a sufficient high exhaust temperature and the engine was manufactured after 1994.

At this time, soot filters are still in the development phase. They are being custom manufactured for each job. It is expected that as the market develops, filters will be readily available in most of the sizes applicable to common DoD engines. Along with this increased availability, the filter costs should also decrease. Since it is expected that all model year 2007 engines will come with some form of exhaust after-treatment, it would be expected that the soot filter market would be fully mature by that time.

6.4 OTHER SIGNIFICANT OBSERVATIONS

Except as otherwise discussed in this and the final report, the project team is not aware of other major factors that can affect implementation of the technology. For situations where implementation is optional, the total cost for implementation will be the driving factor.

Once a DoD activity decides that reducing diesel engine PM emissions is important, they should contract the equipment purchase directly with the suppliers listed below.

Fleetguard Nelson Emission Solutions
1900 McKinley Avenue M/C 50111
Columbus, IN 47201
812-377-3745 (voice)
812-377-2021 (fax)
P.O.C. Amy R. Boerger
Retrofit Sales Executive
Email: Amy.R.Boerger@Fleetguard.com
http://www.cummins.com
(Supplier of passive soot filters)

Rypos, Inc.
3 Industrial Park Road
Medway, MA 02053
(508) 533-9655 (voice)
(508) 533-9656 (fax)
P.O.C. Frank DePetrillo
Chief Operating Officer
Email: fd@rypos.com
http://www.rypos.com/
(Supplier of electrically regenerated soot filters)

The soot filters are proprietary patented hardware, therefore, it may be appropriate to employ sole source procurement.

6.5 LESSONS LEARNED

During the completion of this project, several important lessons were learned. These lessons are:

1. Tests instrumentation installed on moving vehicles needs to be very robust. During the demonstration, most of the originally installed thermocouples broke. Periodically throughout the demonstration they were replaced with new more robust Omega model TJ36-CAIN-18U- SB-OST-M Type-K thermocouples.

2. The Campbell Scientific Model 21X Dataloggers used to record the exhaust pressure and temperature data require the use of eight D-cell batteries. During all of the monthly inspection and data downloading trips, these batteries were replaced. During the inspection trips at the beginning of the project, it was found that several of the data loggers had failed because of a lack of electric power. After investigating the problem, it was found that the cause was the poor quality of the new batteries. To resolve the problem, a different brand of batteries (i.e., Kodak) were used, and all the new batteries were tested prior to use.

3. During the demonstration, numerous test vehicles experienced mechanical and electric failures that caused the vehicles to be removed from service. No one cause or trend could be identified, however, most of the failures occurred at Fort Irwin. It is speculated that the reasons for these increased breakdowns had to do with the extreme environmental conditions experienced at the fort. Given the amount of time that the test vehicles were out of service, it is important to include duplicate test vehicles whenever possible.

4. For the original round of PM emissions testing performed on the Camp Pendleton buses, the University of Utah used an Optical Particle Counter among other test instrumentation. It was found that this instrument did not provide results consistent with the other instruments. During subsequent testing this instrument was not used.

5. During the original round of PM emissions testing performed on the Camp Pendleton buses, the vehicles were tested at load on a dynamometer. Unfortunately, this dynamometer was not designed for extended testing periods. During the tests, numerous retreads separated from the tires. This problem caused a significant testing delay and was expensive since the project was required to pay for the replacement tires. In subsequent testing, large fans and water-cooling was used to reduce heat-up of the tires. This cooling reduced, but did not eliminate the replacement of bus tires.

6.6 END-USER ISSUES

The 10 demonstration engines used during this project were all located at DoD facilities within California. Most of the test vehicles are owned by the General Services Administration (GSA) and leased to the DoD operator. One of the buses located at Camp Pendleton is, however, owned by the Marine Corps. The Air Force tactical gen-sets are controlled by a product manager located at Warner Robins Air Force Base, Georgia. For potential future installations, it is expected that these same parties would be involved.

Prior to starting the demonstration, agreements to participate were made with each of the field activities. When requested, the NFESC principal investigator also contacted GSA and the product manager. In order to support the demonstration, the field activities were asked to operate their engines under their normal duty cycles throughout the demonstration period. In addition, they were asked to take the engines off-line for approximately two hours per month so that the project team could perform an inspection and download engine exhaust temperature and pressure data from the installed data logger. Hardware installations and removal was performed by a combination of project team members, with Marine Corps heavy-duty diesel mechanics assisting with the CSF work.

6.7 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

This project was initiated to address the problem of PM air emissions from DoD diesel engines. Starting with the 2007 model year, diesel engine manufacturers will be required to reduce their engine PM emissions by 90%. In order to achieve this reduction, it is expected that the manufacturers will need to incorporate with their engines some form of exhaust after-treatment such as soot filters. In addition, the EPA and particularly CARB, are evaluating new regulations that would require existing diesel engines to be modified in order to reduce their PM emissions.

For this project, the soot filters were installed in place of the existing engine mufflers. Since no part of the existing engine pollution control systems were changed, the project was completed without obtaining any environmental air permits or the approval of an environmental regulatory agency. During the project, the principal investigator did, however, involve both the EPA and CARB. Early in the project, an EPA group working on non-road diesel engine air emissions regulations were supplied the results of the field screening. At that time, they were considering a new regulation to require the widespread use of passive soot filters. The project's screening data helped to convince

them that this proposal was not practical. During the past year, NFESC has established a working relationship with CARB in order to explore areas of mutual interest. One result of this was CARB's agreement to perform an emissions test on one of the Camp Pendleton buses. The results from this test may be used as a basis for future regulations.

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7.0 REFERENCES

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3. Naval Facilities Engineering Service Center and Cummins, Inc., (2002), “Final Report for Reduction of Diesel Engine Particulate Emissions Using a Self-Regenerating Soot Filter”.

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APPENDIX A

POINTS OF CONTACT

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